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# Respiration and emissions of methane and nitrous oxide from a boreal peatland complex comprising different land-use types

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Greenhouse gas (GHG) emissions from pristine peatlands and peatlands drained for agriculture, forestry or peat extraction have been studied intensively. However, few studies have compared GHG emissions from peatlands under different land-use type within the same peatland area. This study examined methane ($CH_4$) and nitrous oxide ($N_2O$) emissions and respiration ($CO_2$) from a peatland complex in northern Finland, including a peatland used for grass cultivation, a *Pinus sylvestris* and *Betula pubescens* dominated forested peatland, a peat-extraction site and a pristine mire. Gas fluxes were measured in 2011 and 2012 with chambers during the snow-free period, and using the snow-gradient method in winter 2012/2013. Soil respiration was highest in the cultivated site (median during growing season 350 mg $CO_2$ $m^{-2}$ $h^{-1}$), and lower in the forest site and in the peat-extraction site (median for growing season 49 and 130 mg $CO_2$ $m^{-2}$ $h^{-1}$, respectively). The peat-extraction site and the cultivated site were large sources of $N_2O$ during the growing season (median 89 and 28 $\mu$g $m^{-2}$ $h^{-1}$, respectively) and during the winter (median 56 and 460 $\mu$g $m^{-2}$ $h^{-1}$, respectively). The pristine site was a large source of $CH_4$ during the growing season (median 0.98 mg $m^{-2}$ $h^{-1}$), whereas $CH_4$ emissions from the drained sites during the growing season were minor. However, during winter, the peat-extraction site and the cultivated site emitted $CH_4$ (median 0.58 and 0.029 mg $m^{-2}$ $h^{-1}$, respectively). The cultivated site had the highest estimated $CO_2$ equivalent emissions, due to the high $CO_2$ and $N_2O$ fluxes, but the peat-extraction site also had large annual emissions, mainly as $N_2O$. The study suggests that rising groundwater level from 60 to 40 cm could potentially mitigate the emissions from the cultivated site.

## Introduction

Pristine peatlands store large quantities of carbon, which stresses their important role in the global carbon cycle. After peatland drainage, aerobic decay of accumulated soil organic matter begins, often turning a drained peatland area into a source of carbon dioxide ($CO_2$) (Turunen *et al*. 2008). Nutrient-rich peatlands may become sources of nitrous oxide ($N_2O$) when drained (Martikainen *et al*. 1993) and especially if used for cultivation, although high $N_2O$ emissions can

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also occur from some peat-extraction sites (Salm *et al*. 2012). $N_2O$ is nearly 300 times more powerful greenhouse gas (GHG) than $CO_2$ in a 100-year time horizon (Solomon *et al*. 2007). $N_2O$ is produced in soils mainly by microbial activities, nitrification and denitrification being the key processes (Priemé and Christensen 2001). Cultivated peatlands are often large sources of $CO_2$ (Maljanen *et al*. 2010a) and peat extraction areas are sources of $CO_2$ even when burning of the produced peat is not accounted for (e.g. Alm *et al*. 2007, Shurpali *et al*. 2008). Peatland forests can be either long-term net sources or net sinks for $CO_2$ depending on carbon uptake regulated by e.g. soil fertility, drainage intensity and location of the site. In the long-term, nutrient-poor forest soils are more often $CO_2$ sinks and fertile forest soils are more often $CO_2$ sources (Ojanen *et al*. 2013). In the short-term, fertile forests also are net carbon sinks due to carbon accumulation as biomass (Ojanen *et al*. 2013). $N_2O$ emissions from peatland forests are variable, depending on the nutrient status of the forest, but are usually lower than those from cultivated peat soils (Alm *et al*. 2007, Maljanen *et al*. 2010b, 2014, Ojanen *et al*. 2010). As the availability of oxygen in peat increases, the emissions of methane ($CH_4$) decrease, resulting from a decrease in anaerobic $CH_4$ production and an increase in activity of $CH_4$-oxidising microbes in the aerated soil. $CH_4$ emissions from well-drained peatlands are rarely high (e.g. Alm *et al*. 2007, Minkkinen *et al*. 2007, Maljanen *et al*. 2010a, Ojanen *et al*. 2010), but poorly drained forest soils can emit similar amounts of $CH_4$ to pristine mires (Ojanen *et al*. 2010).

Peatlands in the Nordic countries and overall in Europe have been extensively drained (Joosten and Clarke 2002). For instance, in Finland, almost 62% of the peatland area has been drained, mostly for forestry (5.7 million ha) but also for agriculture (Turunen *et al*. 2008). Cultivated peatlands have been estimated to contribute as much as 8% of the total anthropogenic $CO_2$ and 25% of total anthropogenic $N_2O$ emissions in Finland (Forsius *et al*. 1996). As drained peatlands are such an important contributor to GHG emissions in the boreal region, it is important for sustainable land management to understand the reasons for the differences in emission rates between land uses and how changes in environmental conditions, such as groundwater level, contribute to these emissions. It has been suggested that rising the groundwater level of drained peatlands would mitigate GHG emissions; specific to cultivated peatlands, maximum mean groundwater table depth of 30 cm has been suggested (Renger *et al*. 2002, van de Riet *et al*. 2013).

There are many studies on GHG emissions from peatlands drained for agriculture, forestry and peat extraction (*see* e.g. Maljanen *et al*. 2010a, Ojanen *et al*. 2010, 2013, Mander *et al*. 2012, Salm *et al*. 2012), but few studies comparing GHG fluxes under different land-use types in a particular area. Such studies are useful when environmental impacts of different land uses are compared, as differences among peatland sites can be large due to peat type and climate as well as drainage and management practices. In this study, the effect of spatial variations in climate and in pre-drainage peat properties on soil and ecosystem $CO_2$ efflux (respiration from bare peat soil, $R_{soil}$; respiration from soil and plants, $R_{tot}$) and $N_2O$ and $CH_4$ emissions was minimised by choosing sites under different land-use types adjacent to each other inside the same peatland complex.

The aim of this study was to evaluate differences in GHG fluxes among peatland areas under different land-use types (differences in drainage intensity, vegetation cover, peat physical properties and peat nutrient content). The first hypothesis was that the intensively drained sites with deeper mean groundwater level (cultivated site and the peat-extraction site) would result in higher soil respiration, higher $N_2O$ emissions, and lower $CH_4$ emissions, compared with the less intensively drained site (the forest site and the pristine mire). The second hypothesis was that soil temperature, groundwater depth, change in biomass (in the cultivated site) and soil moisture content significantly explain temporal variation in gas fluxes.

## Material and methods

### Study sites

The study sites are located in the boreal area of

northern Finland (N 7152690 E 470243 in ETRS-TM35FIN; Fig. 1) and are part of the Pelso peatland complex, which was partly drained from the late 1800s onwards. The drained area, originally more fen type than the nutrient-poor pristine bog, is currently used for forestry, crop cultivation and peat extraction. The peat in the cultivated site and the forest site is mainly *Carex* peat, but in the peat-extraction site it is a mixture of *Sphagnum* and *Carex* types. The degree of humification (von Post) is between 3 and 8 for the uppermost 30 cm of soil in all drained study sites (Table 1).

The pristine site is a nutrient-poor bog with the peat depth of 1.5–2.0 m. The uppermost 60 cm of the peat layer is almost undecomposed *Sphagnum* moss with high C/N (100 in the top 0–15 cm layer) (Table 1). Three study plots with one collar each were established at the pristine site: one in a wet hollow (Pristine A) and two on top of a hummock (Pristine B and C), as the site is a mosaic of these two vegetation types.

The forest site was drained from a mire in the 1970s and currently dominated by pine (*Pinus sylvestris*) and birch (*Betula pubescens*), with ground vegetation comprising e.g. mosses and shrubs [dwarf shrub type (Vatkg) in the Finnish forest classification system according to Laine *et al*. (2012)]. The trees show poor growth due to the shallow groundwater table and, presumably, lack of nutrients (Table 1). No fertilizer or lime has been applied in the area, and the peat is only moderately decomposed. Peat depth at the site is approximately 1.5 m. The average distance between the drainage ditches (approx. 70 cm deep) is 30 m and to our knowledge, ditches have not been maintained since the original drainage. The groundwater level between the ditches is shallow, less than 10 cm below the soil surface at times, which enables formation of water pools and occurrence of plant species typical of wet conditions, such as *Rhododendron tomentosum*. Three study plots were established at the forest site, one in the wetter part of the forest (Forest A) and two in the drier part (Forest B and C), each with one collar in the mid-point of its own strip (15 m from ditches). In study plots Forest A and C, a 1.5 m × 1.5 m non-vegetated area was established with one collar in it, about 3 m away from the location of the collar for $R_{tot}$ measurement.

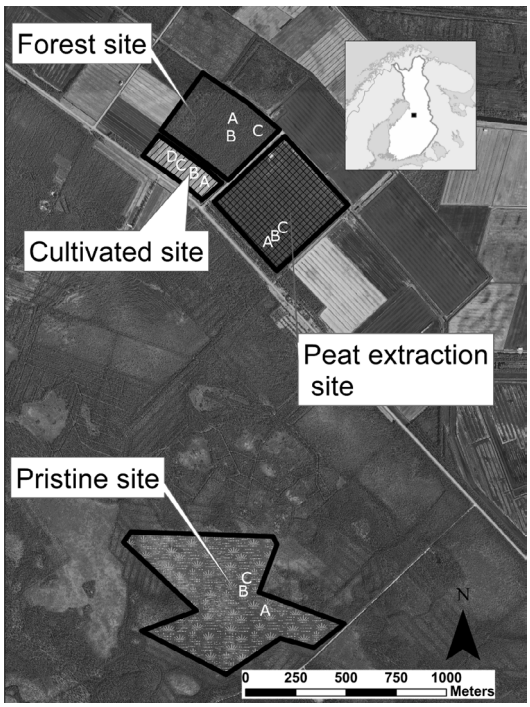


**Fig. 1**. Aerial view the Pelso peatland, showing the four study sites under different land uses. Study plot locations are marked with capital letters. Aerial photograph ©National Landsurvey of Finland; modified with permission from the copyright owner.

Above-ground plant parts and the litter layer had been removed from the non-vegetated areas one week before the beginning of the gas-flux measurements in 2012 and above-ground plant parts were removed by hand weekly after each gas-flux measurements.

The cultivated site was drained for agriculture in the 1930s and it has been under a rotation of timothy grass (*Phleum pratense*) (three to four years) and barley (*Hordeum vulgare*) (one year) ever since. In the study years (2011 and 2012), timothy grass was growing at the site. The site has been ditched to 70 cm depth (distance between ditches 15–30 m) and in 2012 had a peat depth ranging from 1.4 to over 1.5 m. Mineral soil was added to the peat to enhance the cultivation properties when the area was taken for cultivation. The site has been limed (median pH 6.7 in the uppermost 15 cm of peat and 4.8 in the 45–60 cm layer) and is fertilised for grass production twice a year with chemical fertiliser (in 2012 with 125 kg N $ha^{-1}$, of which 50% as

$NH_4$-N and 50% as $NO_3$-N, and 23 kg K $ha^{-1}$). During the barley growing years, the site is fertilised with cow manure (30 t $ha^{-1}$ $y^{-1}$) in spring at sowing. In addition, when the site is ploughed after grass cultivation, cow manure is added (20 t $ha^{-1}$ in September 2012) in preparation for barley cultivation in the following year. Grass in the cultivated site was harvested in weeks 24 and

**Table 1**. Physical properties of upper topsoil (0–15 cm depth) and lower subsoil (45–60 cm depth) in different land use areas of the Pelso peatland. Decomp. degree = degree of decomposition (von Post scale), BD = bulk density, OM = organic mater content, $\theta$ = soil water content. %-vol. = percentage of volume, %-mass = percentage of mass, bdl = $NO_2$-N content below detection limit of 0.01 $\mu$g $g^{-1}$.

| Land use | | Depth 0–15 cm | | | | Depth 45–60 cm | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | *n* | Min. | Max. | Mean | *n* | Min. | Max. | Mean |
| Forest | Decomp. degree | 3 | 3 | 5 | 4 | 4 | 3 | 6 | 4 |
| | BD (mg $cm^{-3}$) | 5 | 110 | 160 | 140 | 5 | 100 | 130 | 120 |
| | Porosity (%-vol.) | 5 | 82 | 91 | 86 | 5 | 81 | 90 | 86 |
| | OM (%-mass) | 14 | 96 | 98 | 97 | 14 | 97 | 98 | 97 |
| | pH (median) | 5 | 4.0 | 4.5 | 4.3 | 4 | 4.8 | 5.2 | 5.0 |
| | $\theta$ (%-vol.) | 84[a] | 31 | 95 | 63 | 7 | 79 | 88 | 81 |
| | C/N | 3 | 14 | 17 | 16 | 3 | 17 | 19 | 18 |
| | $P_{tot}$ (mg $kg^{-1}$) | 6 | 860 | 980 | 910 | 6 | 280 | 470 | 390 |
| | $N_{tot}$ (%-mass) | 3 | 3.1 | 3.6 | 3.4 | 3 | 2.9 | 3.1 | 3.0 |
| | $NO_3$-N ($\mu$g $g^{-1}$) | 4 | 0.2 | 0.79 | 0.4 | bdl | bdl | bdl | bdl |
| | $NH_4$-N ($\mu$g $g^{-1}$) | 4 | 71 | 95 | 80 | – | – | – | – |
| Cultivated | Decomp. degree | 8 | 4 | 4 | 4 | 4 | 4 | 5 | 5 |
| | BD (mg $cm^{-3}$) | 9 | 410 | 590 | 500 | 7 | 130 | 170 | 150 |
| | Porosity (%-vol.) | 9 | 63 | 76 | 70 | 7 | 81 | 88 | 84 |
| | OM (%-mass) | 19 | 30 | 53 | 41 | 18 | 88 | 97 | 93 |
| | pH (median) | 8 | 5.9 | 6.8 | 6.7 | 6 | 4.6 | 5.6 | 4.8 |
| | $\theta$ (%-vol.) | 99[a] | 43 | 71 | 61 | 7 | 77 | 83 | 70 |
| | C/N | 4 | 13 | 15 | 14 | 4 | 19 | 24 | 21 |
| | $P_{tot}$ (mg $kg^{-1}$) | 6 | 1300 | 1700 | 1600 | 6 | 840 | 1100 | 940 |
| | $N_{tot}$ (%-mass) | 4 | 1.5 | 2.1 | 1.8 | 4 | 2.2 | 2.7 | 2.5 |
| | $NO_3$-N ($\mu$g $g^{-1}$) | 2 | 6.1 | 7.1 | 6.6 | bdl | bdl | bdl | bdl |
| | $NH_4$-N ($\mu$g $g^{-1}$) | 2 | 2.5 | 6.4 | 4.4 | – | – | – | – |
| Peat extraction | Decomp. degree | 12 | 4 | 8 | 5 | 12 | 4 | 7 | 5 |
| | BD (mg $cm^{-3}$) | 5 | 140 | 230 | 190 | 4 | 120 | 150 | 140 |
| | Porosity (%-vol.) | 5 | 77 | 88 | 84 | 4 | 85 | 96 | 91 |
| | OM (%-mass) | 16 | 92 | 98 | 95 | 16 | 96 | 99 | 97 |
| | pH (median) | 4 | 4.5 | 5.2 | 4.8 | 3 | 5.0 | 5.5 | 5.3 |
| | $\theta$ (%-vol.) | 80[a] | 33 | 75 | 57 | 10 | 70 | 87 | 75 |
| | C/N | 3 | 16 | 19 | 18 | 3 | 25 | 27 | 26 |
| | $P_{tot}$ (mg $kg^{-1}$) | 6 | 470 | 660 | 570 | 6 | 500 | 690 | 600 |
| | $N_{tot}$ (%-mass) | 3 | 2.8 | 3.2 | 2.9 | 3 | 2.0 | 2.2 | 2.1 |
| | $NO_3$-N ($\mu$g $g^{-1}$) | 4 | 1.1 | 36 | 15 | bdl | bdl | bdl | bdl |
| | $NH_4$-N ($\mu$g $g^{-1}$) | 4 | 120 | 270 | 170 | – | – | – | – |
| Pristine | Decomp. degree | 7 | 1 | 2 | 1 | 5 | 2 | 3 | 2 |
| | BD (mg $cm^{-3}$) | 3 | 47 | 55 | 51 | 3 | 52 | 77 | 65 |
| | Porosity (%-vol.) | 3 | 94 | 97 | 96 | 3 | 97 | 100 | 100 |
| | OM (%-mass) | 10 | 97 | 100 | 99 | 9 | 97 | 99 | 98 |
| | pH (median) | 4 | 4.0 | 4.3 | 4.1 | 3 | 3.8 | 4.1 | 3.9 |
| | $\theta$ (%-vol.) | 55[a] | 49 | 99 | 83 | 3 | 73 | 100 | 89 |
| | C/N | 4 | 76 | 400 | 100 | – | – | – | – |
| | $P_{tot}$ (mg $kg^{-1}$) | 6 | 200 | 620 | 370 | 4 | 290[b] | 430[b] | 330[b] |
| | $N_{tot}$ (%-mass) | 4 | 0.35 | 0.59 | 0.47 | – | – | – | – |
| | $NO_3$-N ($\mu$g $g^{-1}$) | 4 | 0.0 | 0.090 | 0.04 | bdl | bdl | bdl | bdl |
| | $NH_4$-N ($\mu$g $g^{-1}$) | 4 | 1.7 | 19 | 9.6 | – | – | – | – |

[a] Determined with Degacon EC-$H_2O$ Soil Moisture Sensor EC-5 during gas flux measurements in 2011 and 2012.
[b] Depth 14–60 cm.

32 in 2011 and in weeks 26 and 34 in 2012. Four study points were established at the cultivated site (Cultivated A, B, C and D), each with one collar in the mid-point of a strip. In study plots Cultivated C and D, a 1.5 m × 1.5 m non-vegetated area was established with one collar within it, about 2 m away from the location of the collar for $R_{tot}$ measurement. Plants and 5–10 cm of surface soil (to remove most of the grass roots) were removed from the non-vegetated areas one week before the beginning of the gas flux measurements in 2012, and above-ground plant parts by hand weekly after gas flux measurements.

The peat-extraction site was drained to about 1–1.5 m depth having 20 m drain spacing (collector ditch is lower than 1.5 m) in 2006 and peat production started in 2007. Before extraction, the site was a poorly-drained forested peatland. The soil surface has subsided about 50 cm following the loss of buoyancy after lowering of the groundwater table. In addition, during the four years of extraction until 2010, about 40 cm of the peat was harvested. For this reason, the exposed peat layer at this site is not equivalent to the topmost peat layer at the cultivated and forest sites. At the measurement location, peat extraction ended after summer 2010 (due to wind erosion of peat and dust transport affecting a nearby farm). Three study plots were established at the peat-extraction site (Peat extraction A, B and C), each with one collar in the mid-point between the ditches (10 m from the ditch).

## Environmental variables and soil characteristics

Soil temperature ($T_s$) at 5 cm depth, soil volumetric water content ($\theta$) at 7 cm depth (Degacon EC-$H_2O$ Soil Moisture Sensor EC-5), and air temperature ($T_a$) were determined concurrently with the gas flux measurements. Groundwater depth (WT) was measured continuously (logging interval: 10 min) with loggers (Solinst® Levelogger Gold, TrueTrack WT-HR 1000) in groundwater pipes (inner diameter 52 mm) in 2011 and 2012. $T_a$ at each study site and $T_s$ at 5 cm depth at each study plot were monitored (logging interval: 30 min) with iButton® loggers (Thermochron DS1922L, Thermochron DS1921G-F5, Hygrochron DS1923) in 2012 (due to logger failures at Pristine C, the data from Pristine B were used in calculations; in the forest and at the cultivated site, data from different study plots with removed vegetation were combined to get uninterrupted series for the calculations). Beside traditional measurements of the environmental parameters, infrared aerial photography was used to assess small-scale variation in surface temperatures — and thus potentially in gas fluxes — of the drained sites. Surface temperature of the drained study sites was measured once during the growing season in 2013 with an infrared photography method using a Thermo Vision A40 sensor (Korkka-Niemi *et al*. 2012). After increasing contrast, the infrared photographs were converted from RGB to grayscale using GIMP 2.8.10 (GNU Image Manipulation Program). The growing seasons in 2011 and 2012 were 22 April–7 October and 6 May–10 October, respectively (long-term average timing of growing season (1981–2010) was 3 May–9 October). Precipitation (744 mm in 2011 and 743 in 2012) during both years exceeded long-term average of 620 mm (Pirinen *et al*. 2012). The annual average air temperatures were 3.3 °C and 1.7 °C in 2011 and 2012, respectively, while the long-term average was 1.9 °C (Pirinen *et al*. 2012).

Total phosphorus in soil was determined using hydrochloric acid (HCl) extraction (Andersen 1976). Total carbon and nitrogen in peat were measured with an elemental analyser (Thermo Electron Corporation). $NO_3^-$ was extracted from the peat with Milli-Q-$H_2O$ (1:3 v/v) and analysed with an ion chromatograph (DX 120, Dionex Corporation, USA). $NH_4^+$ was extracted with 1 M potassium chloride (KCl) (1:3 v/v) and analysed with a spectrophotometer (Ultrospec 3000 Pro, Biochrom, UK) based on the method of Fawcett and Scott (1960). Nitrogen forms ($NH_4^+$, $NO_3^-$ and $NO_2^-$) were determined from soil samples taken in June 2013 (at the cultivated site the samples were taken from the part that was at the time under grass cultivation). The average height of grass ($L_g$) (maximum length of the above-ground part of the plant, $n$ = 12) at the cultivated site was determined on the days when the gas fluxes were measured. In 2012, the dry biomass of each harvest from the cultivated site was estimated by

cutting grass from four 0.5 m × 0.5 m squares and drying at 65 °C for 48 hours. Dry bulk density, porosity and soil water content were determined from samples taken with sharpened steel cylinders (diameter 4 cm, volume 50 $cm^3$), saturated and dried at 70 °C for 24 h and 105 °C overnight. Organic matter content was determined by incineration at 550 °C. Soil pH was determined from a soil–deionised-water solution (1:2.5).

## $CO_2$, $N_2O$ and $CH_4$ flux measurements

Gas fluxes were measured with a closed static-chamber technique during the snow-free period in 2011 and 2012 (weekly) and by measuring gas gradients in snow during the winter 2012/2013 (three occasions) (*see* Table 2). PVC collars (depth in soil 5–10 cm) were installed at each study plot one week before the measurements started in the spring, and closed with chambers (opaque PVC, diameter 30 cm, total volume including collar 26–39 l, with a fan installed inside the chamber) during gas flux measurements. $R_{tot}$ of plants and soil included respiration from above-ground parts of plants, roots, the rhizosphere, soil microbes and soil fauna but did not include the above-ground parts of the trees in the forest. $R_{soil}$ was measured as $CO_2$ flux from bare peat-soil in the areas within study plots from which the plants were removed. Note that for the peat-extraction site, $R_{soil} = R_{tot}$ as there was no vegetation present.

$R_{tot}$ and $R_{soil}$ were calculated based on the rate of linear $CO_2$ concentration increase in the chamber (determined from air pumped through a VAISALA CARBOCAP® Carbon Dioxide Probe GMP343 device in closed circulation) between 2 and 7 minutes after closing the chamber, taking into account the air temperature and humidity inside the chamber during the measurement. This sampling time was selected to avoid errors due to disturbance during and directly after installation of the chamber and due to the decline in $CO_2$ flux to the chamber if the sampling time exceeds 15 min. Too long sampling time and the consequent high $CO_2$ concentration inside the chamber causes a decrease in concentration gradient between soil air and the chamber (Heinemeyer and McNamara 2011). With 7-min sampling time, there were no signs of decreasing flux towards the end of the period. Of all chamber measurements of $R_{tot}$ or $R_{soil}$ ($n$ = 353) at the study sites (excluding Pristine A where this method was not applicable with the applied closure time due to very low $R_{tot}$, hence the measurements were excluded from the study), 80% of correlations of time with gas concentration within the chamber had $r^2 >$ 0.85. The measurements with smaller $r^2$ were included if there was no indication of error such as obviously non-linear increase in gas concentration upon visual inspection (45 however were discarded), as almost all of them were the measurements where the resulting $R_{tot}$ or $R_{soil}$ value was low (max. 350 mg $CO_2$ $m^{-2}$ $h^{-1}$, mean 58 mg $CO_2$ $m^{-2}$ $h^{-1}$), and excluding them would thus have skewed the results.

Measurements of $N_2O$ and $CH_4$ (total number = 254) were made with additional stainless-steel chambers (diameter 30 cm, height 30 cm) covered with a gas-tight plastic lid with two holes closed with 25 mm rubber septa. Additional chambers

**Table 2**. Study setup; study plots = number of study plots (the total number of measurements per study site in parentheses), collars = number of collars per study plot.

| | | Pristine mire | Cultivated site | Forest site | Peat-extraction site |
|---|---|---|---|---|---|
| $R_{soil}$ | study plots | | 2 (26) | 2 (28) | |
| | collars | | 1 | 1 | |
| $R_{tot}$ | study plots | 3 (34) | 4 (94) | 3 (82) | 3 (78) |
| | collars | 1 | 1 | 1 | 1 |
| $CH_4$ | study plots | 2 (46) | 2 (57) | 2 (66) | 2 (66) |
| | collars | 2* | 2* | 2* | 2* |
| $N_2O$ | study plots | 2 (46) | 2 (57) | 2 (66) | 2 (66) |
| | collars | 2* | 2* | 2* | 2* |

* One PVC collar + chamber and one stainless steel chamber without collar.

were twisted into the soil before gas flux measurements and removed afterwards. Gas samples of 30 ml were taken with a 60-ml polypropylene syringe (Terumo) at 5, 10, 15 and 25 min after closing the chambers, from the headspace of the chamber. The samples were injected within 24 hours into pre-evacuated 12-ml vials (Labco Excetainer®) and analysed for $N_2O$ and $CH_4$ with a gas chromatograph (Agilent 6890N, Agilent Technologies, USA) equipped with an autosampler (Gilson, USA), electron capture (ECD) and flame ionisation (FID) detectors for $N_2O$ and $CH_4$, respectively. Compressed air containing 0.836 $\mu$l l$^{-1}$ $N_2O$ and 2.02 $\mu$l l$^{-1}$ $CH_4$ was used for daily calibration. The flux rates were calculated from the linear increase or decrease in gas concentration in the headspace of the chamber with time. If there were any indications of failures in the gas sampling or gas analysis, the results were excluded (13 cases). Measured $N_2O$ and $CH_4$ fluxes were converted into $CO_2$ equivalents using multipliers 298 and 25, respectively, in order to account for their respective global warming potentials in 100 years. In the discussion, the GHG emissions of different sites were compared as $CO_2$-eq. emissions.

During winter, when the snow depth exceeded 10 cm, $CO_2$, $N_2O$ and $CH_4$ fluxes were determined by measuring gas concentration gradients between the snow and ambient air and by calculating associated diffusion rates in the snow from the snowpack density (Maljanen *et al*. 2003). Gas samples (30 ml) were drawn with a stainless steel probe (∅ 3 mm, length 100 cm) from the snow close to the chamber locations. Simultaneously, snow samples were collected with a PVC tube (∅ 10.2 cm) for porosity measurements. The intact samples were weighed for calculation of the average porosity of snow using the density of pure ice (0.9168 g cm$^{-3}$). In winter, a total of 16 measurements were made at the forest site (5 of them over non-vegetated soil), 18 at the cultivated site (12 over ploughed soil, and for comparison, 6 measurements over vegetated study plot where barley had been growing in the summer), and 12 at the peat-extraction site.

## Soil gas concentrations

The concentrations of $CH_4$ and $N_2O$ in the soil were measured to assess production of the gases in soil as gas production is not necessarily reflected in fluxes to the atmosphere due to processes such as oxidation in the topsoil. The gas concentrations were measured using silicon tubes (∅ 1.0 cm, wall thickness 0.3 cm, length 110 cm, $V$ = 86 cm$^3$, buried to a depth of 20 cm from the soil surface. The gas samples (30 ml) were taken through a sampling line with a syringe and the $CH_4$ and $N_2O$ concentrations were analysed as described above. There were two silicone tubes at four study plots (Forest A and C, Cultivated C and D) from 15 May to 23 October 2012, except when the tubes were removed from the cultivated site during harvest or ploughing.

## Statistical analyses

For statistical analysis, the momentary gas-flux rates were log-transformed to normalise the data and make the variances more homogeneous across the study sites and plots; the variances, however, were not entirely equal after the log-transformation but this did not show as alarming in model diagnostics. For log-transformation of negative values, a constant (2 for $CH_4$, 100 for $N_2O$) was added to the flux rates before the transformation. The effects of environmental variables on $CO_2$ gas flux rates was tested by using them as fixed effects in a linear model constructed using Linear Mixed-Effects Models (*lme*) in R (correlation structure AR(1); random effects: study plot for environmental variables). The effects of environmental variables on $N_2O$ and $CH_4$ gas-flux rates were tested by using them as fixed effects in a linear model constructed using Generalized Least Squares (*gls*) in R (correlation structure AR(1); random effect: study plot) (Pinheiro *et al*. 2015) as this approach does not assume equal variances of errors. Differences in fluxes among study plots or among land-use types were also tested by using the study plots or land-use types as fixed effects in a *gls* model (correlation structure AR(1), rank-transformed gas fluxes as dependent variables). Significance of differences in continuously measured WT and $T_s$ among land-use types was tested using a Kruskal-Wallis test and the post-hoc Tukey-Kramer-Nemenyi

test (*posthoc.kruskal.nemenyi.test* in the *PMCMR* package of R (Pohlert, 2015). A Kruskall-Wallis test can be assumed applicable when the ratio of the greatest to the smallest variance does not exceed 4 (Howell 2002); this applied for $T_s$ but not WT whose to ration of the greatest to the smallest variance was 4.8. Correlations between gas-flux rates and environmental factors were evaluated using Spearman's rank-order correlation. Correlation was considered moderate when $|r| > 0.4$ and strong when $|r| > 0.6$.

The statistical analyses were performed either with R (ver. 3.1.1) or the IBM SPSS ver. 21.0 software (IBM Corp.).

## Calculated emissions over the growing season 2012

As $R_{tot}$ and $R_{soil}$ generally increase with soil temperature (e.g. Koizumi *et al*. 1999, Minkkinen *et al*. 2007, Ojanen *et al*. 2010), it was important to calculate $R_{tot}$ and $R_{soil}$ between gas-flux measurements to account for the temporal variation in the fluxes due to changing conditions at the study sites. The response of respiration ($R$) to soil temperature at 5 cm depth ($T_s$) can be expressed as follows (Lloyd and Taylor 1994):

$$R = R_{ref} e^{B\left[1/\left(T_{5,ref} - T_{5,0}\right) - 1/\left(T_s - T_{5,0}\right)\right]}, \quad (1)$$

where $B$ is the fitted coefficient and $T_{5,0}$ = –46.02 °C (the theoretical temperature where $R$ = 0, according to Lloyd and Taylor 1994). The soil temperature of 10 °C was chosen as the reference temperature ($T_{5,ref}$). Note that according to Eq. 1, the increase in respiration with increasing soil temperature is not quite exponential, as the rate of change in respiration decreases with increasing temperature. Equation 1 can, therefore, be reformulated into:

$$\ln R = \ln R_{ref} + B \times T_{s,mod} \quad (2)$$

where modified $T_s$ ($T_{s,mod}$) is used instead of measured $T_s$:

$$T_{s,mod} = [1/(T_{5,ref} - T_{5,0}) - 1/(T_s - T_{5,0})]. \quad (3)$$

In some cases, respiration is affected by water table depth (WT) (e.g. Glenn *et al*. 1993, Mäkiranta *et al*. 2009) or vegetation biomass (Flanagan and Johnson 2005). With WT, the following can be formed based on Eq. 2:

$$\ln R = B_0 + B_1 T_{s,mod} + B_2 WT + B_3 T_{s,mod} WT. \quad (4)$$

Thus, to better take the variation in $CO_2$ fluxes into account, a regression model based on Eq. 4 was used to calculate continuous $R_{tot}$ and $R_{soil}$ rates for the growing season of 2012. Regression model coefficients were calculated for each land-use type using the linear mixed model (*lme* in the *nlme* package (ver. 3.1–120) (Pinheiro *et al*. 2015) in R, using study plot as pooling factor (random = 1|Study plot) (*see* Table 3 for parameter estimates). Working Correlation Matrix Structure was AR(1) [corCAR1(form = ~date)] for $R_{tot}$ at the cultivated, peat-extraction and forest sites, and "independent" for $R_{tot}$ at the pristine site and $R_{soil}$ at the forest site and the cultivated site. For the peat-extraction site, the value measured on 23 October 2012 ($n$ = 3) was excluded as this data point was outside the modelled period, and the relationship between soil respiration and soil temperature at these very low soil temperatures (0.7–1.2 °C) seemed to differ from the general trend at temperatures above 5 °C. The Nash-Sutcliffe Efficiency (Nash and Sutcliffe 1970) of the regression model predictions was 0.83 (0.38–0.71 for each individual land-use type model) (Fig. 2). 95% prediction intervals (95%PI) for the predictions were calculated for predicted $\ln R_{tot(soil)}$ using the *predict.SE* function of the *AICcmodavg* package (Mazerolle 2015) as follows:

$$95\%\text{PI} = \text{predicted value} \pm 1.96\text{SE2} \quad (5)$$

$$\text{where SE2} = (\text{SE}^2 + \sigma)^{1/2}, \quad (6)$$

where SE is the standard error of the predicted value and $\sigma$ is the residual variance of the model. As there were only two measuring dates after ploughing of soil at the cultivated site, the variation in measured respiration in the ploughed soil could not be well-explained by the measured environmental variables and no reasonable model could be fitted. Thus, the mean value of the measured fluxes was used for estimating respiration at the cultivated site during the period after

ploughing of soil. To estimate the cumulative respiration for the site, minimum and maximum of the measured values were used for calculating a rough estimate for a lower and upper limits of cumulative respiration during this period.

The growing-season emissions of $N_2O$ and $CH_4$ were calculated based on monthly mean emissions as their variation could not be well explained by the measured environmental variables, except for the cultivated site before the ploughing of soil. For that period, the $N_2O$ emissions decreased roughly linearly with time that passed since the latest fertilization ($F_T$) so the $N_2O$ emissions were calculated using $F_T$ as predictor in a model formed with the *gls* function in R (study point as random intercept, Working Correlation Matrix Structure = AR(1)) ($p$ ($F_T$) < 0.0001, parameter estimate (SE) = –0.016 (0.0034) in the model formed). If median emission rates of $N_2O$ were used for calculations, the emissions would have been considerably lower for the peat-extraction site due to non-normal distribution of the data (especially high outlier emission rates of $CH_4$ and $N_2O$).

## Results

### Differences in environmental conditions among land-use types

There were significant differences in continuously-measured WT and $T_s$ among the study sites during the frost-free season (Kruskal-Wallis test:

**Table 3**. Parameters for Eq. 4; $r$ = Spearman's correlation between the variable and ln$R_{tot}$ or $R_{soil}$, Lower and Upper = 95%CLs for the parameter estimate, $B$ = parameter estimate, $p$ = significance of the parameter for the model; $I$ = intercept, $T_{s,mod}$ = transformed (Eq. 3) soil temperature at 5 cm depth, WT = groundwater depth, $T_{s,mod} \times$ WT = interaction term.

| | $r$ | Lower | Upper | $B$ | $p$ |
|---|---|---|---|---|---|
| Forest, plants removed | | | | | |
| B0 ($I$) | | 2.44 | 3.88 | 3.16 | < 0.001 |
| B1 ($T_{s,mod}$) | 0.51 | –325 | 630 | 152 | 0.514 |
| B2 (WT) | 0.45 | –0.00124 | 0.0584 | 0.0286 | 0.059 |
| B3 ($T_{s,mod} \times$ WT) | 0.62 | –11.4 | 33.1 | 10.8 | 0.325 |
| Forest, plants not removed | | | | | |
| B0 ($I$) | | 4.77 | 5.34 | 5.05 | < 0.001 |
| B1 ($T_{s,mod}$) | 0.59 | 91.7 | 437 | 264 | 0.003 |
| B2 (WT) | 0.37 | 0.00155 | 0.0208 | 0.0112 | 0.024 |
| B3 ($T_{s,mod} \times$ WT) | 0.67 | –2.57 | 13.3 | 5.39 | 0.181 |
| Cultivated, plants not removed | | | | | |
| B0 ($I$) | | 6.31 | 5.53 | 5.92 | < 0.001 |
| B1 ($T_{s,mod}$) | 0.59 | 1130 | 530 | 829 | < 0.001 |
| B2 (WT) | 0.26 | 0.0181 | 0.00446 | 0.0113 | 0.002 |
| B3 ($T_{s,mod} \times$ WT) | 0.62 | –1.53 | –12.2 | –6.84 | 0.012 |
| Cultivated, plants removed | | | | | |
| B0 ($I$) | | 0.00849 | 4.19 | 2.1 | 0.049 |
| B1 ($T_{s,mod}$) | 0.61 | –419 | 1270 | 427 | 0.299 |
| B2 (WT) | 0.46 | 0.0356 | 0.087 | 0.0613 | < 0.001 |
| B3 ($T_{s,mod} \times$ WT) | 0.65 | –19.8 | 9.8 | –4.98 | 0.484 |
| Peat extraction | | | | | |
| B0 ($I$) | | 2.07 | 4.38 | 3.23 | < 0.001 |
| B1 ($T_{s,mod}$) | 0.69 | –856 | 459 | –199 | 0.549 |
| B2 (WT) | 0.06 | 0.000542 | 0.0267 | 0.0136 | 0.042 |
| B3 ($T_{s,mod} \times$ WT) | 0.70 | 0.554 | 18.6 | 9.59 | 0.038 |
| Pristine | | | | | |
| B0 ($I$) | | 5.88 | 3.92 | 4.9 | < 0.001 |
| B1 ($T_{s,mod}$) | 0.51 | 716 | –99.7 | 308 | 0.133 |
| B2 (WT) | 0.24 | 0.0202 | –0.0462 | –0.013 | 0.429 |
| B3 ($T_{s,mod} \times$ WT) | 0.52 | 20.3 | –10.9 | 4.69 | 0.544 |

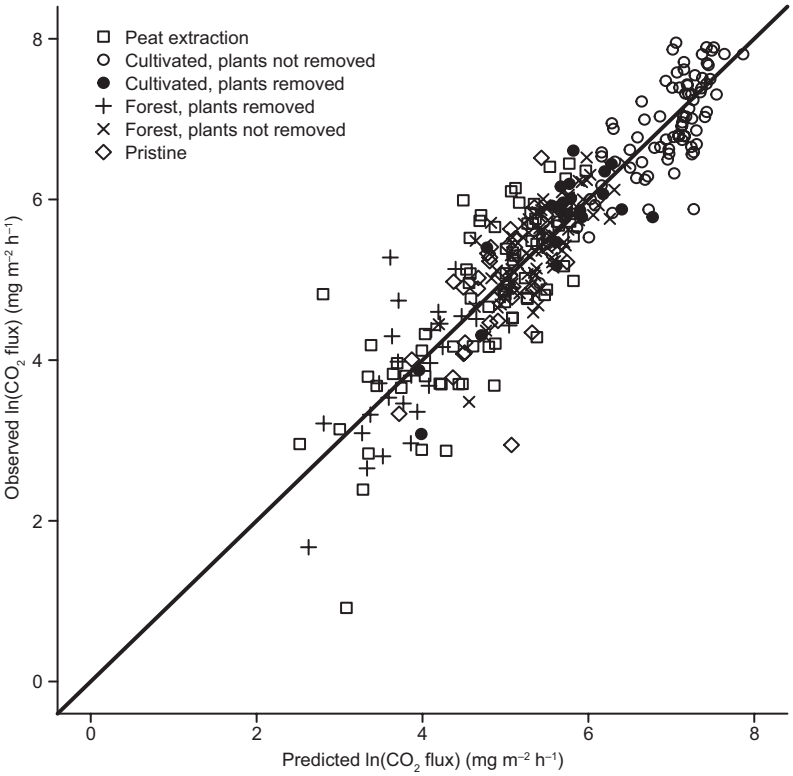


**Fig. 2**. Correlation between calculated (Eq. 4) and measured $CO_2$ exchange at the study sites in the Pelso peatland. Note that data are ln-transformed.

for WT, $\chi^2_3 = 29939.45$, $p < 0.0001$, $n = 46676$; for $T_s$, $\chi^2_3 = 457.4258$, $p < 0.0001$, $n = 42992$). During 2012, WT was significantly (Tukey-Kramer-Nemenyi test, $p < 0.0001$) deeper at the peat-extraction site (mean WT ± SD = 68 ± 23 cm, $n$ = 11 052) than at the cultivated site (55 ± 15 cm, $n$ = 14 736) where it was significantly ($p < 0.0001$) deeper than at the forest site (22 ± 10 cm, $n$ = 11 052). Also, WT was significantly ($p < 0.0001$) deeper at all the drained sites than at the pristine site (15 ± 13 cm, $n$ = 9836). $\theta$ was higher at 45–60 cm depth (Table 1) and more variable in the topsoil at the pristine site (top-soil $\theta$'s SD = 27%-points) and the forest site (SD = 14%-points) as compared with the cultivated site (SD = 5.8%-points) and the peat-extraction site (8.6%-points) (Table 1).

Mean soil temperature (5 cm depth) in 2012 was significantly (Tukey-Kramer-Nemenyi test, $p < 0.0001$) lower at the forest site (mean $T_s$ ± SD = 11.3 ± 3.1 °C, $n$ = 11 052) than at the cultivated site (12.0 ± 3.6 °C, $n$ = 14 736), peat-extraction site (12.1 ± 4.1 °C, $n$ = 11 052) and the pristine site (12.1 ± 4.5 °C, $n$ = 6152). Surface temperature of the peat-extraction site on a sunny day was higher (mean 38 °C) than that at the cultivated site (mean 24 °C) and the forest site (mean 27 °C) (*see* Appendix). Surface temperature at the forest site had large spatial variation, apparently due to variation in the density of vegetation. The surface temperature was more uniform at the cultivated and peat-extraction sites, but ploughing and peat extraction had left the soil surface with grooves in the driving direction whose surface temperature was lower than the that of the surroundings (difference of up to 10 °C). The temperatures in the ditches differences greatly among the sites: at the peat-extraction site, the deep, sharp-edged ditches, half in shadow, showed up as cooler areas, whereas at the cultivated site, the shallow ditches were warmer than the cultivated surface.

## Differences in gas emissions among land-use types

The measured $R_{tot}$ rates were significantly

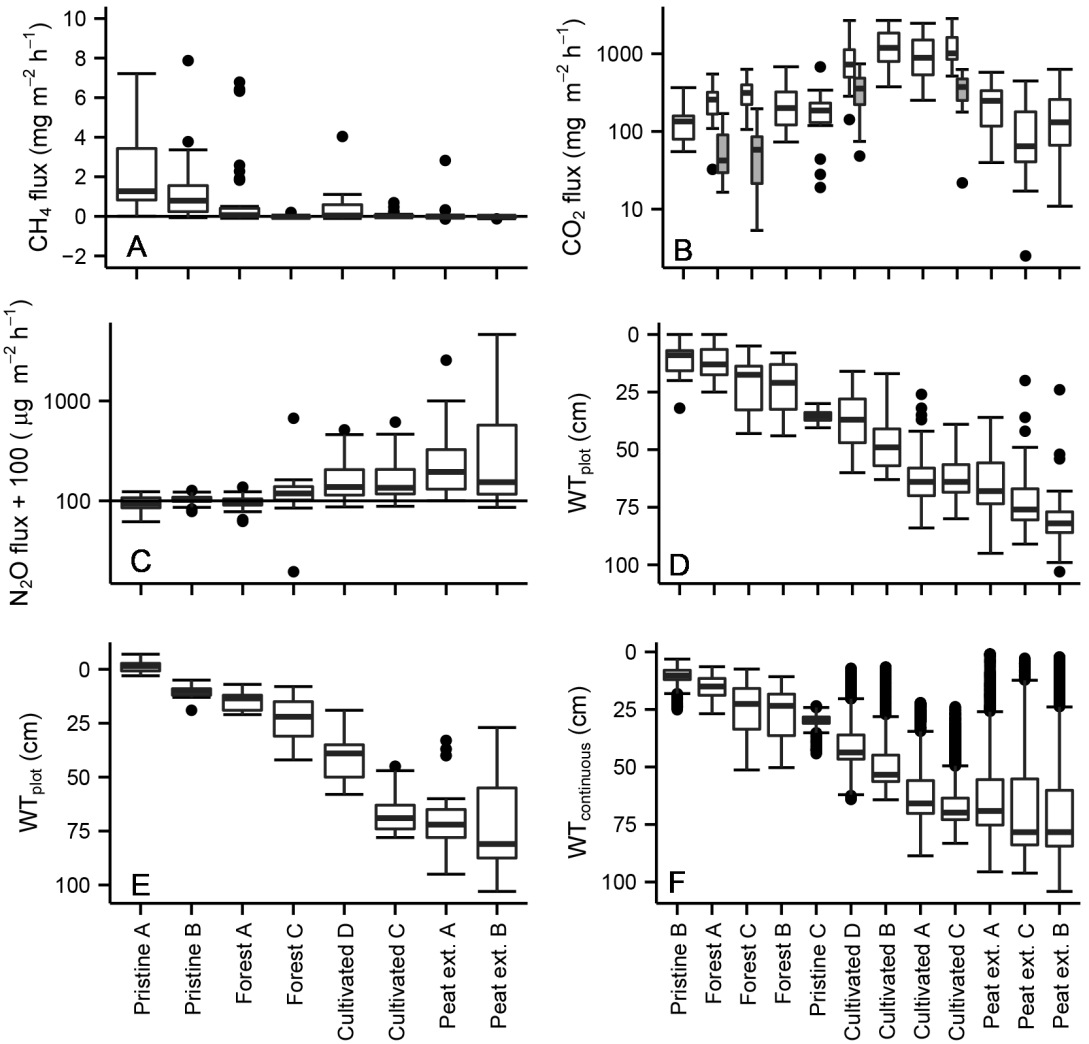


**Fig. 3**. Observed (**A**) $CH_4$ flux, (**B**) total ($R_{tot}$) and soil ($R_{soil}$) respirations rates, (**C**) $N_2O$ flux, and at the study plots, and groundwater depths (**D**–**E**) at the study plots ($WT_{plot}$) measured during $CO_2$ gas flux measurements (**D**) and during $N_2O$ and $CH_4$ gas flux measurements (**E**), and (**F**) groundwater depths measured continuously ($WT_{continuous}$). Peat ext. refers to the peat-extraction site. In **B**, two high values (18 mg $CH_4$ $m^{-2}$ $h^{-1}$ for Cultivated D and 58 mg $CH_4$ $m^{-2}$ $h^{-1}$ for Pristine B) were left out. Bottom and top of the boxes are 1st and 3rd percentiles, and lines within boxes are medians, t whiskers show interquartile ranges multiplied by 1.5 (or maximum and minimum values if those would be closer to median).

($p < 0.0001$) higher at the cultivated site than in the other land-use types (Fig. 3b and Table 4). Soil respiration rates ($R_{soil}$) at the cultivated site were significantly higher than at the peat-extraction ($p = 0.0012$) and forest sites ($p < 0.0001$) (Fig. 4 and Table 4). At the pristine site, $R_{tot}$ at Pristine B and C were low (Fig. 3b and Table 4) and at Pristine A it was so small that it could not be measured reliably with the chamber method. The calculated mean cumulative $R_{tot}$ values (Eq. 4) for the study period in 2012 (17 May–16 October), which was close to the growing season in that year (7 May–2 October), were 34 t $CO_2$ $ha^{-1}$, 9.3 t $CO_2$ $ha^{-1}$ and 5.8 t $CO_2$ $ha^{-1}$ for the cultivated, the forest and pristine sites, respectively. The calculated cumulative $R_{soil}$ was 11, 2.0 and 4.5 t $CO_2$ $ha^{-1}$, for the cultivated, forest and peat-extraction site, respectively.

At all sites, $R_{tot}$ and $R_{soil}$ varied seasonally (Fig. 4). The measured respiration rates as well

as emissions calculated with Eq. 4 increased from May to the end of July and decreased towards autumn. At the cultivated site, the $R_{tot}$ values decreased after harvest and thereafter increased again with increasing grass biomass. The same amount of dry biomass (3 t ha$^{-1}$) was harvested during the first cut (30 June 2012) and the second cut (20 August 2012). In the winter, $CO_2$ emission rates were relatively high at the cultivated site, especially in January (up to 750 mg $CO_2$ m$^{-2}$ h$^{-1}$) and the peat-extraction site, and low at the forest site (Table 4).

The peat-extraction site and, to a lesser extent, the cultivated site were large sources of $N_2O$ (Table 4), but as is typical for $N_2O$ emissions, the variation of emission rates was great as well. The emissions from the peat-extraction site were significantly ($p = 0.030$) higher than from the cultivated site where emissions were significantly ($p < 0.0001$) higher than from the forest and pristine sites (Fig. 5). The emissions rates from the peat-extraction site were particularly high, exceeding 1000 $\mu$g $N_2O$ m$^{-2}$ h$^{-1}$ several times during the growing season. $N_2O$ fluxes from the cultivated site increased clearly after each addition of the N fertiliser and while most of this increase lasted for about 1–2 weeks, there was a somewhat decreasing trend in the $N_2O$ emission rates after each fertilisation until the next one (Fig. 5). The $N_2O$ concentrations in soil pore-air peaked at the values as high as 112 $\mu$l l$^{-1}$ (after the first fertilisation) and 14 $\mu$l l$^{-1}$ (after the second fertilisation), but returned to < 5.0 $\mu$l l$^{-1}$ in two weeks. An exceptional high $N_2O$ concentration was measured on 24 July. The wintertime emissions from the cultivated site and the peat-extraction site were considerable (Table 4). The forest site was a negligible source or even a sink for $N_2O$ during both the growing season and the winter (Table 4). The $N_2O$ concentrations in the forest soil pore-air were consistently close to the ambient concentration (0.33 $\mu$l l$^{-1}$), and were at most 0.39 $\mu$l l$^{-1}$. The emissions of $N_2O$ from the pristine site were small.

**Table 4**. Measured fluxes of $CO_2$, $N_2O$ and $CH_4$ at the Pelso peatland. *n* = number of measurements, nd = no data, vegetation intact = vegetation at the cultivated site before ploughing.

| Land use | Treatment | Growing season | | | | Winter | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | *n* | Median | Min | Max | *n* | Mean | Median | Min | Max |
| **$CO_2$ (mg m$^{-2}$ h$^{-1}$)** | | | | | | | | | | |
| Cultivated | Vegetation intact | 94 | 920 | 140 | 2800 | 6 | 170 | 150 | 82 | 330 |
| | After ploughing | 11 | 210 | 38 | 650 | 12 | 210 | 100 | 6.3 | 750 |
| Cultivated | Vegetation removed | 26 | 370 | 22 | 740 | nd | nd | nd | nd | nd |
| Forest | Vegetation intact | 82 | 253 | 33 | 680 | 11 | 28 | 22 | 24 | 51 |
| Forest | Vegetation removed | 28 | 49 | 5.3 | 200 | 5 | 13 | 11 | 8.8 | 23 |
| Pristine | Vegetation intact | 34 | 143 | 19 | 677 | nd | nd | nd | nd | nd |
| Peat extraction | Bare soil | 78 | 134 | 2.5 | 630 | 12 | 45 | 37 | 16 | 96 |
| **$CH_4$(mg m$^{-2}$ h$^{-1}$)** | | | | | | | | | | |
| Cultivated | Vegetation intact | 53 | 0.041 | –0.11 | 18 | 6 | 1.8 | 1.9 | 0.50 | 3.4 |
| | After ploughing | 16 | –0.013 | –0.053 | 0.052 | 12 | 0.040 | 0.029 | –0.025 | 0.13 |
| Cultivated | Vegetation removed | nd | nd | nd | nd | nd | nd | nd | nd | nd |
| Forest | Vegetation intact | 73 | 0.011 | –0.10 | 6.8 | 11 | 0.23 | 0.0083 | –0.014 | 1.9 |
| Forest | Vegetation removed | nd | nd | nd | nd | 5 | 0.0030 | 0.0038 | –0.011 | 0.020 |
| Pristine | Vegetation intact | 46 | 0.98 | –0.067 | 58 | nd | nd | nd | nd | nd |
| Peat extraction | Bare soil | 66 | –0.020 | –0.13 | 2.8 | 12 | 2.6 | 0.58 | 0.071 | 16 |
| **$N_2O$ (µg m$^{-2}$ h$^{-1}$)** | | | | | | | | | | |
| Cultivated | Vegetation intact | 53 | 28 | –13 | 510 | 6 | 3.7 | 4.3 | –3.1 | 7.0 |
| | After ploughing | 16 | 130 | 11 | 360 | 12 | 1800 | 460 | 5.3 | 8300 |
| Cultivated | Vegetation removed | nd | nd | nd | nd | nd | nd | nd | nd | nd |
| Forest | Vegetation intact | 73 | 4.0 | –80 | 570 | 11 | 0.76 | 0.40 | –1.4 | 6.9 |
| Forest | Vegetation removed | nd | nd | nd | nd | 5 | –0.21 | –0.29 | –0.79 | 0.38 |
| Pristine | Vegetation intact | 46 | 1.4 | –38 | 27 | nd | nd | nd | nd | nd |
| Peatextraction | Bare soil | 66 | 89 | –14 | 4500 | 12 | 130 | 56 | 8.6 | 400 |

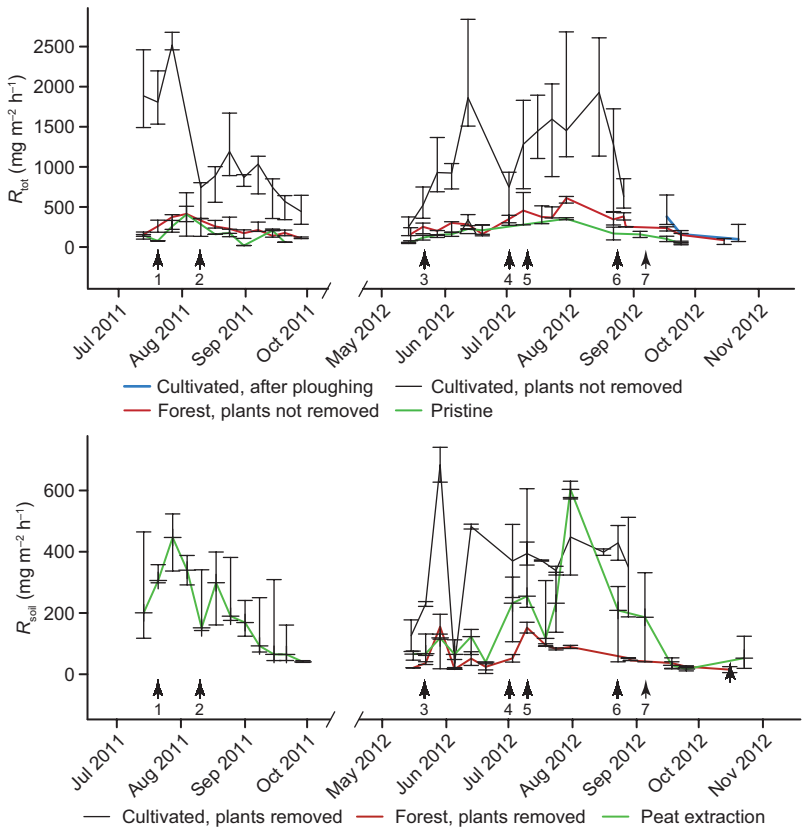


**Fig. 4**. (Upper panel) Measured median soil respiration ($R_{soil}$) and (lower panel) total respiration ($R_{tot}$) at the study sites under different land uses at the Pelso peatland in 2011 and 2012. Whiskers show minimum and maximum of measured values. Arrows with numbers show timing of cultivation activities at the cultivated site (1 = harvest, 2 = harvest, 3 = fertilization, 4 = fertilization, 5 = harvest, 6 = harvest, 7 = ploughing of soil and fertilization with manure).

Only the pristine site was clearly an important source of $CH_4$ during the growing season (Table 4 and Fig. 3a). The forest site was a small source of $CH_4$ regardless of season, and during the growing season there was no significant difference in $CH_4$ emissions from the cultivated and forest sites. However in winter, the peat-extraction site and to a lesser extent, the cultivated site (median emission rate 0.029 mg $CH_4$ m$^{-2}$ h$^{-1}$ from the part ploughed and fertilized in the autumn, 1.9 mg $CH_4$ m$^{-2}$ h$^{-1}$ from the vegetated part where barley was cultivated during summer) emitted some $CH_4$. Methane concentrations were high (mean = 22 000 $\mu$l l$^{-1}$, maximum = 130 000 $\mu$l l$^{-1}$) in the soil (20 cm depth) of the 'wet' study plot in the forest (Forest A) as compared with those of the cultivated site (mean = 21 $\mu$l l$^{-1}$, maximum = 100 $\mu$l l$^{-1}$) and with very low concentrations (mean = 2.5 $\mu$l l$^{-1}$, maximum = 3.9 $\mu$l l$^{-1}$) in the 'dry' study plot (C) in the forest.

## Relationship among environmental variables and gas emissions

The wettest study plot at the cultivated site, (Cultivated D, $WT_{av}$ = 40 cm), had lower measured $R_{tot}$ and $R_{soil}$ rates than the driest study plots at that site (Cultivated C, $WT_{av}$ = 65 cm), but the difference was not statistically significant. There was no statistically significant difference in the measured $N_2O$ emission rates between Cultivated C and D, either. The calculated (Eq. 4) total respiration, however, was lower in the "wet" study plot (cumulative $R_{tot}$ 36 t $CO_2$ ha$^{-1}$ *vs*. 30 t $CO_2$ ha$^{-1}$ in the "dry" study plot). In the winter, $N_2O$ emissions from Cultivated C were higher (median 900 $\mu$g $N_2O$ m$^{-2}$ h$^{-1}$, mean 2800 $\mu$g $N_2O$ m$^{-2}$ h$^{-1}$) than those from Cultivated D (median 360 $\mu$g $N_2O$ m$^{-2}$ h$^{-1}$, mean 730 $\mu$g $N_2O$ m$^{-2}$ h$^{-1}$). At the forest site, there was no significant difference in $R_{soil}$ rates between the wettest study plot (Forest A, $WT_{av}$ = 16 cm), and

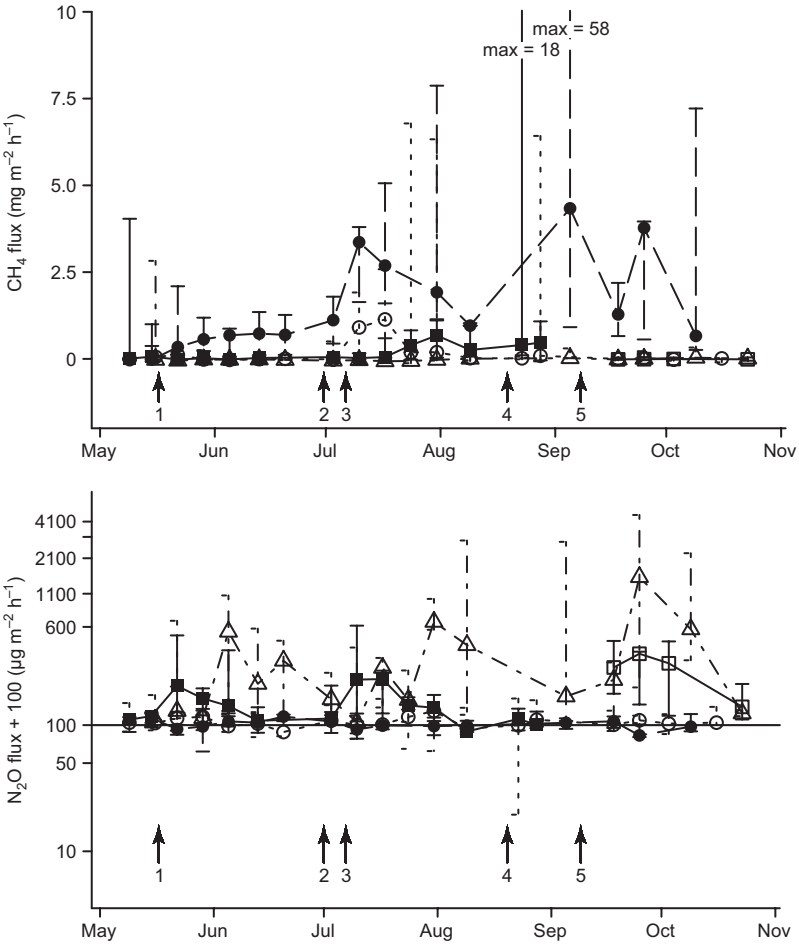


**Fig. 5**. (Upper plot) Measured median $N_2O$ and (lower plot) $CH_4$ emissions at the drained study sites under different land uses in the Pelso peatland in observation season in 2012. Whiskers show minimum and maximum of measured values. Arrows with numbers show timing of cultivation activities at the cultivated site (1 = fertilization, 2 = fertilization, 3 = harvest, 4 = harvest, 5 = ploughing of soil and fertilization with manure).

the drier study plot (Forest C, $WT_{av}$ = 25 cm). The calculated total and soil respirations in the growing season were lower at Forest A (cumulative $R_{tot}$ 8.6 t $CO_2$ $ha^{-1}$ and cumulative $R_{soil}$ 1.8 t $CO_2$ $ha^{-1}$) than at Forest C (cumulative $R_{tot}$ 11 t $CO_2$ $ha^{-1}$ and cumulative $R_{soil}$ 2.3 t $CO_2$ $ha^{-1}$). At the pristine site, $R_{tot}$ at a hollow (Pristine A) was too low to measure with the chamber method but most likely very low even as compared with the low emissions from the two study plots on top of the hummocks (Pristine B and C).

Methane emissions were smaller with deeper $WT_{av}$. During the growing season, the emission rates ($p < 0.0001$, $n = 73$) and the soil pore-air concentrations ($p = 0.001$, $n = 27$) of methane at the 'wet' study plot Forest A were significantly higher than at the 'dry' study plot Forest C. Also, the methane emission rates at Forest A were higher in winter. Within the cultivated site, the emission from the 'wet' Cultivated D were significantly higher at $p < 0.1$ ($p = 0.070$, $n = 69$) than from the 'dry' Cultivated C.

The measured $R_{tot}$ values at the drained sites were best explained by $T_{s,mod}$ or $T_{s,mod} \times WT$ interaction, but WT was significant for modelling $R_{tot}$ as well (Table 3). $R_{soil}$ increased with increasing $T_{s,mod}$ ($r$ = 0.50–0.67) in all the studied land-use types (Fig. 6), but $T_{s,mod}$ was not significant for modelling $R_{tot}$ if WT was included. Volumetric water content did not correlate with or explain the variation in any of the measured gases. As expected, vegetation biomass represented by $L_g$ was a significant predictor (parameter estimate ± SE = 0.0138 ± 0.00498, $p = 0.0094$) for $R_{tot}$ at the cultivated site (data of the year 2012). No clear connection was found between $T_s$ (range

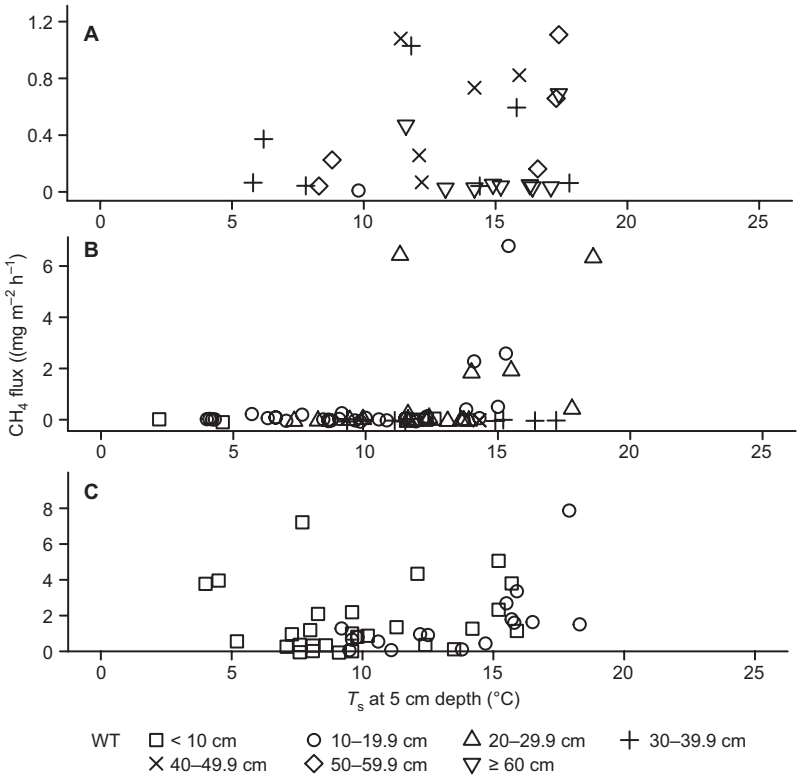


**Fig. 6**. Effect of soil temperature ($T_s$) and groundwater depth (WT) on $CH_4$ fluxes in the cultivated site (A), the forest (B) and the pristine site (C) in the Pelso peatland. Two outliers were left out from (A) to increase readability.

0.7–23.7 °C) and $N_2O$ emissions. For the cultivated site, the time passed since last fertilization ($F_T$) was so significant ($p = 0.0001$) for predicting $N_2O$ emissions that it hid any possible effects of WT or $T_s$. Effect of $T_s$ on $CH_4$ emissions was not straightforward. All the highest (over 1.8 mg $CH_4$ $m^{-2}$ $h^{-1}$) emissions from the wet study plot in the forest (Forest A) were measured in July and August when $T_s$ at 5 cm was higher than 11 °C, but also emissions as low as 0.1 mg $CH_4$ $m^{-2}$ $h^{-1}$ were measured at $T_s$ higher than 11 °C and similar WT (Fig. 6). The same effect was seen, to an extent, at the cultivated site, where the variation in $CH_4$ emissions was much greater at $T_s > 11$ °C (Fig. 5). Especially the $CH_4$ emissions from the 'wet' study plot D increased slightly with increasing soil temperatures in July (Fig. 5), but there was a time lag in the response to increasing topsoil temperatures. Time from fertilization was the most significant variable for predicting $CH_4$ emissions ($p = 0.027$). $CH_4$ emissions from the pristine site seemed to respond to higher soil temperature as well, but when WT was less than 10 cm deep, high emissions occurred at low temperatures as well (Fig. 6). $T_s$ and WT correlated weakly in most study plots except for Forest C ($r = 0.52$) and Cultivated D, ($r = 0.50$).

## Discussion

### Total emissions as $CO_2$-eq. were high from cultivation and the peat extraction area

$CO_2$ emission from the system to the atmosphere at the cultivated site were considerable. According to Grønlund *et al*. (2006), in Nordic conditions the gross primary production (GPP) of a cultivated grassland site can be calculated by multiplying grass yield by a factor of 2.5, which is in line with observations by Maljanen *et al*. (2001). Assuming, as Grønlund *et al*. (2006), that approximately 44% of grass dry biomass is carbon, the carbon yield of the cultivated site would equal 9.7 t $CO_2$ $ha^{-1}$ and GPP 24 t $CO_2$ $ha^{-1}$. The calculated net ecosystem $CO_2$

exchange (NEE = $R_{tot}$ – GPP, where positive NEE means release of carbon to atmosphere) at the cultivated site during the growing season would then be 9.3 t $CO_2$ $ha^{-1}$. Using the NEE estimation (Table 5), 91% of the total GHG emissions from the cultivated site during the growing season were that of $CO_2$, while 7.0% and 1.9% were that of $N_2O$ and $CH_4$, respectively. The measured values of $R_{tot}$ and $R_{soil}$ at the cultivated site were within the range, or somewhat higher, than values reported in the literature for the total respiration of a site cropped with grass (e.g. Maljanen *et al*. 2001, Kløve *et al*. 2010, Berglund *et al*. 2011) and for the soil respiration of an arable site (e.g. Koizumi *et al*. 1999, Maljanen *et al*. 2001). The variation in the measured wintertime $N_2O$ fluxes was high, but the estimated contribution by wintertime $N_2O$ emissions to the annual GHG emissions of the cultivated site was most likely substantial, even as high as the estimated GHG emissions of the growing season. The wintertime $N_2O$ emissions from the ploughed and manure-fertilized side of the cultivated site were much higher than the $N_2O$ emissions from the non-ploughed site with barley during summer. In addition, the $CO_2$ emissions were higher and $CH_4$ emissions lower from the ploughed side of the field. This suggest large differences in wintertime emissions between years according to phase of the crop rotation. More $CH_4$ was likely oxidized in the recently ploughed and thus better aerated soil than in the undisturbed, vegetation-covered soil. The manure fertilization, lack of plants taking up nitrogen and more available nitrate and carbon after ploughing in autumn are likely reasons for the high $N_2O$ and $CO_2$ emissions from the ploughed study plots. While there is an uncertainty due to emission rates having been measured only three times during the winter, similar or higher winter $CO_2$ emissions (Maljanen *et al*. 2001), $N_2O$ emissions (e.g. Maljanen *et al*. 2010b, Regina *et al*. 2004) and $CH_4$ emissions (e.g. Alm *et al*. 1999, Regina *et al*. 2007) from boreal peatland ecosystems have previously been observed.

Besides the cultivated site, the peat-extraction site produced large GHG emissions. During the growing season, $N_2O$ and $CO_2$ were emitted in almost equal quantities when converted to $CO_2$ equivalent emissions, and the $N_2O$ emissions from the peat-extraction site were many times higher than those from the cultivated site. In addition, the site emitted both $N_2O$ and $CH_4$ during the winter. The measured $N_2O$ emissions from the peat-extraction site were more than 20 times higher than those reported previously (e.g. Alm *et al*. 2007, Hyvönen *et al*. 2009), although Salm *et al*. (2012) observed high $N_2O$ emissions from some of their mined peatland study sites. The measured values of $R_{soil}$ at the peat-extraction site were in the range or somewhat higher than the values reported earlier for peat extraction areas (Shurpali *et al*. 2008, Mander *et al*. 2012, Salm *et al*. 2012). The peat extraction and culti-

**Table 5**. Calculated cumulative fluxes of the greenhouse gases (GHG) $N_2O$, $CH_4$ and $CO_2$ in different land-use areas of the Pelso peatland during the growing season. For the $N_2O$ and $CH_4$ emissions, values calculated using highest and lowest measured monthly values are given in parentheses; for the $CO_2$ emissions, 95% prediction intervals are given in parentheses. Cumulative $R_{tot}$ for the pristine site was calculated based on study plots Pristine B and C.

| Study site | $CO_2$-eq. $N_2O$ (t $ha^{-1}$) | $CO_2$-eq. $CH_4$ (t $ha^{-1}$) | Cumulative $R_{tot}$ (t $ha^{-1}$) | Cumulative $R_{soil}$ (t $ha^{-1}$) | net $CO_2$ (t $ha^{-1}$) | net GHG as $CO_2$-eq. (t $ha^{-1}$) |
|---|---|---|---|---|---|---|
| Forest | 0.12 (–0.19 to 0.66) | 0.34 (–0.039 to 1.3) | 9.3 (6.0 to 14) | 2.0 (1.1 to 4.1) | nd | nd |
| Cultivated | 0.71 (0.42 to 2.9) | 0.19** (0.033 to 2.4) | 34* (24 to 48) | 11* (1.2 to 150) | 9.3* (0.88 to 29) | 10 |
| Pristine | 0.0055 (–0.15 to 0.13) | 1.5 (0.39 to 3.6) | 5.8 (1.9 to 17) | nd | nd | nd |
| Peat extraction | 5.7 (0.27 to 16) | –0.0047 (–0.066 to 0.11) | 4.5 (1.2 to 14) | 4.5 (1.2 to 14) | 4.5 (1.2 to 14) | 10 |

* assumes respiration after ploughing of soil as observed for the study plots outside the non-vegetated plots.
** one obvious outlier, emission rate 18 mg $CH_4$ $h^{-1}$ $m^{-2}$, excluded from calculation.

vated sites both had C/N below 20 and high soil ammonium and nitrate concentrations (Table 1). This explains the high $N_2O$ emission to some extent. While the peat-extraction site was not fertilized, at such newly drained sites, $NO_3$-N concentrations can be high due to high availability of newly-aerated peat and highly-fluctuating groundwater levels promoting nitrogen mineralisation (Kløve 2001). Warming of the peat layer at the peat-extraction site, seen in the infrared photo (Appendix), could partly explain the high soil nitrate concentration and $N_2O$ emissions from that site. Warming can enhance nitrogen mineralisation and nitrification in peat, and therefore increase the $N_2O$ emissions, especially in the absence of plants taking up nitrogen.

GPP was not calculated for the pristine site, but it is likely that the pristine site, being a nutrient-poor boreal mire with low total respiration rate, was, in the short term, either a small source or a sink for $CO_2$ (e.g. Lund *et al*. 2007, Sagerfors *et al*. 2008) and thus had a small climate warming effect, mainly due to the $CH_4$ emissions. GPP of the forest site was not measured in this study, and furthermore, root respiration was not eliminated, since roots were not truncated. Previous studies have reported similar (Glenn *et al*. 1993) or higher (Minkkinen *et al*. 2007, Ojanen *et al*. 2010, 2013) $R_{tot}$ and $R_{soil}$ values for Vatkg-type forests (the similar type as in this study) than those found in this study. The tree growth and consequently, carbon uptake, were likely limited by poor drainage as the optimal groundwater depth for forested peatland is generally considered to be at least 30 cm (e.g. Päivänen and Hånell 2012). However, it is likely that even with poor growth of the trees, with soil respiration rates and $CH_4$ and $N_2O$ emissions as low as they were, our forest site could have a small short-term net climate cooling effect (Ojanen *et al*. 2013). This was despite the fact that all our measurement plots were located at the mid-point of a strip, where the groundwater was shallower than closer to the ditches. Therefore, the $CH_4$ emissions from the study plots likely give an overestimate for the whole site, although the $CH_4$ emissions from the ditches are not known.

The cultivated and peat-extraction sites had high climate-warming effect as compared with the pristine bog and literature values for more nutrient-rich fen type mires (which they were before drainage). Minerotrophic fens can be sources or sinks for $CO_2$ but tend to have a significant, short-term climate warming effect (e.g. up to 5 $CO_2$-eq. t $ha^{-1}$ $a^{-1}$ as modelled by Saarnio *et al*. 2007) due to $CH_4$ emissions (which can vary from almost no emissions to up to 14 $CO_2$-eq. t $ha^{-1}$ $a^{-1}$) (Saarnio *et al*. 2007).

## Differences in drainage intensity explained differences between sites to high extent

The differences in the GHG emissions among study sites could largely be attributed to different drainage intensities required by each management option and their various indirect consequences. The relationship between groundwater depth and GHG emissions was characterised by higher emissions of $N_2O$ and respiration occurring at the study plots with deeper groundwater level, until the effect levelled off at around 60 cm (Fig. 3). The reverse was true for the $CH_4$ emissions which decreased with deeper groundwater level and were absent from the study plots with WT > 60 cm. The thin, oxic layer of peat, due to shallow groundwater table, limited soil respiration at the forest site, and limited nitrification and nitrate formation. This was seen in the low soil nitrate concentrations and thus in low $N_2O$ emissions, even with the low soil C/N (Table 1) which usually favours $N_2O$ emissions (e.g. Klemedtsson *et al*. 2005). In contrast, the high $CO_2$ emissions from the cultivated site were enabled by the groundwater level ($WT_{av}$ = 51 cm) that was within the range reported to be favourable for respiration in drained peat soils (Maljanen *et al*. 2013). At the peat-extraction site, the groundwater level was below 60 cm for most of the time which reduced respiration (Maljanen *et al*. 2013). This can also be seen as higher respiration at Peat extraction A than at the two study plots with deeper WT (Fig. 3b), and probably in the non-linear relationship between WT and $R_{soil}$ at that site (though confounded by the interaction between $T_s$ and WT).

The other effects of land use are hard to separate from the effects of the different drainage

intensities required by each management type, but comparing cultivated and peat-extraction sites with equal WT levels indicates that cultivation as such favours higher $CO_2$ emissions. Also, the considerable $CH_4$ emissions at Cultivated D could not be explained by WT alone. It seems that $CH_4$ oxidation was inhibited at the cultivated site as the median $CH_4$ emissions from the 'wet' study plot (D) were similar to those from the 'wet' study plot in the forest despite the soil $CH_4$ concentrations being several magnitudes smaller at the cultivated site. The forest site was only a minor source of $CH_4$ during all seasons, even with high $CH_4$ production in the deeper layers of peat indicated by high soil $CH_4$ concentrations. This observation indicates efficient $CH_4$ consumption in the top 20 cm of the soil, which seemed to be lacking at the cultivated site, most probably partly because of N fertilization (e.g. Aronson and Helliker 2010). Also, the cultivated site had compacted topsoil (Table 1) and most likely disturbed soil structure and low amount of macropores which both lower gas diffusion and oxygen availability for $CH_4$ oxidisers (Regina *et al*. 2007, Prajapati and Jacinthe 2014). The $CH_4$ emissions from the cultivated site decreased after ploughing, probably due to increased supply of oxygen to the topsoil (although soil temperatures decreased at the same time). At the forest site, the topsoil was more porous and provided better conditions for $CH_4$ oxidation, and most of the large amount of $CH_4$ found in the soil air at 20 cm depth appeared to be consumed before reaching the soil surface. Some of the difference in emissions among the study sites could be caused by other factors such as differences in vegetation types (other than through the effects of vegetation on WT and $T_s$) in nutrient and carbon cycling, or effects of cultivation practices on oxygen, nutrient and carbon availability through increased soil pH (Andersson and Nilsson 2001), tillage (e.g., Gesch *et al*. 2007) and fertilization (Kivimäki *et al*. 2013).

## Effect of environmental parameters on temporal variation in gas fluxes

As expected, $T_{s,mod}$ was the most significant environmental parameter for explaining the variation in $R_{tot}$ within land-use types, except for the pristine site where none of the tested variables were significant for the model. However, deeper WT also caused a significant increase in $R_{tot}$ and was the most relevant variable for explaining variation in $R_{soil}$. This supports the hypothesis that raising groundwater closer to soil surface could mitigate $CO_2$ emissions (e.g. Maljanen *et al*. 2013). Temporal variation in WT had less effect on $CH_4$ or $N_2O$ emissions. Variation in $N_2O$ emissions was not well explained by the studied variables other than the obvious increase in N fertilization at the cultivated site. $CH_4$ emissions increased with $T_s$ (*see* e.g. Lai *et al*. 2009), but the effect was not straightforward, indicating presence of a confounding factor or temperature effect being indirect such as $T_s$ controlling methane emission through its effect on biomass production (Pypker *et al*. 2013, Lai *et al*. 2009). The higher $CH_4$ emissions at the cultivated site during late summer may have been due to the state of the vegetation as indicated by significance of the $L_g$ variable. While the increased emissions continued past harvest, growth of plants between harvests may have shown as higher $CH_4$ emissions due to increase in root exudates (e.g. MacDonald *et al*. 1998). Another reason for the unclear effect of $T_s$ could be the anoxic conditions, needed for $CH_4$ production, normally prevailing in wet soils such as deeper peat layers where temperature is not necessary well correlated with topsoil temperature. Also, $T_s$ may have affected $CH_4$ oxidation and production processes disproportionately.

## Should the groundwater level of the cultivated site and the forest be changed?

There was no statistically significant difference in $N_2O$ emission or $R_{soil}$ rates among the study plots with deeper and shallower $WT_{av}$, neither at the cultivated nor the forest site. However, WT was a significant variable in estimating both $R_{tot}$ and $R_{soil}$. While the calculated cumulative $R_{soil}$ values were similar among the study plots with different mean WT levels, the cumulative $R_{tot}$ values (which accounted for the variation in environmental parameters not caught with the

weekly observations) were lower (as much as by 16%) at the study plot with $WT_{av}$ of 40 cm than at the one with $WT_{av}$ = 65 cm. At the cultivated site where large part of the annual $CO_2$-eq. GHG impact seemed to potentially come from wintertime $N_2O$ emissions, the study plot that had deeper $WT_{av}$ during the growing season emitted much more $N_2O$ in most wintertime measurements than the one with shallow $WT_{av}$. The $CH_4$ emissions were higher with shallower $WT_{av}$ both at the cultivated site and at the forest site, but the $CH_4$ emissions contributed only little to the overall GHG. The potential increase in $CH_4$ emission with shallower groundwater level is most likely not a great concern. Thus, rising the groundwater level at the cultivated site would potentially have at least some long-term mitigating effect on $CO_2$ and $N_2O$ emissions and no substantial harmful effects. At the forest site, however, rising the already shallow groundwater level would likely harm tree growth and thus decrease carbon uptake, so it cannot be recommended.

## Conclusions

Total and soil respiration, methane, and nitrous oxide emissions were measured in drained peatlands with grass cultivation, forestry and peat extraction and in a pristine bog. Based on the results from two growing seasons and one winter, we recommend that following points 1–3 are taken into account in land management, and points 4–5 are considered when estimating greenhouse gas fluxes from drained peatlands:

1. As expected, the cultivated site had clearly the highest annual total GHG emissions, mostly originating from $CO_2$ and $N_2O$. Also, the peat-extraction site had large annual emissions, mainly due to $N_2O$ emission favoured by high soil nitrate concentration. The forest with poor drainage had only small methane and $N_2O$ emissions, and as respiration was low, likely had substantially lower impact on climate than the other drained sites.
2. At the cultivated site, the lower respiration during the growing season combined with the lower winter emissions of $CO_2$ and $N_2O$ at the study plot with 40 cm groundwater level as compared with the one with 65 cm groundwater level suggest that rising groundwater level to 40 cm would potentially decrease the annual GHG emissions. The observed increase in $CH_4$ emissions with shallower $WT_{av}$ had a negligible effect on the total annual GHG emissions.
3. In the forest, the emissions were minor, but groundwater table should be kept at least at the current depth (mean 22 cm) as the wetter parts of the forest seem to have potential for methane emissions, and the wetness of soil is likely limiting tree growth and thus carbon uptake even with the current drainage intensity.
4. Small-scale variation should be taken into account when estimating GHG emissions. The observed variation in soil surface temperature will likely result in spatial variation in the carbon balance and could also have impact on emissions of $CH_4$ and $N_2O$.
5. Winter emissions have to be taken into account in management.

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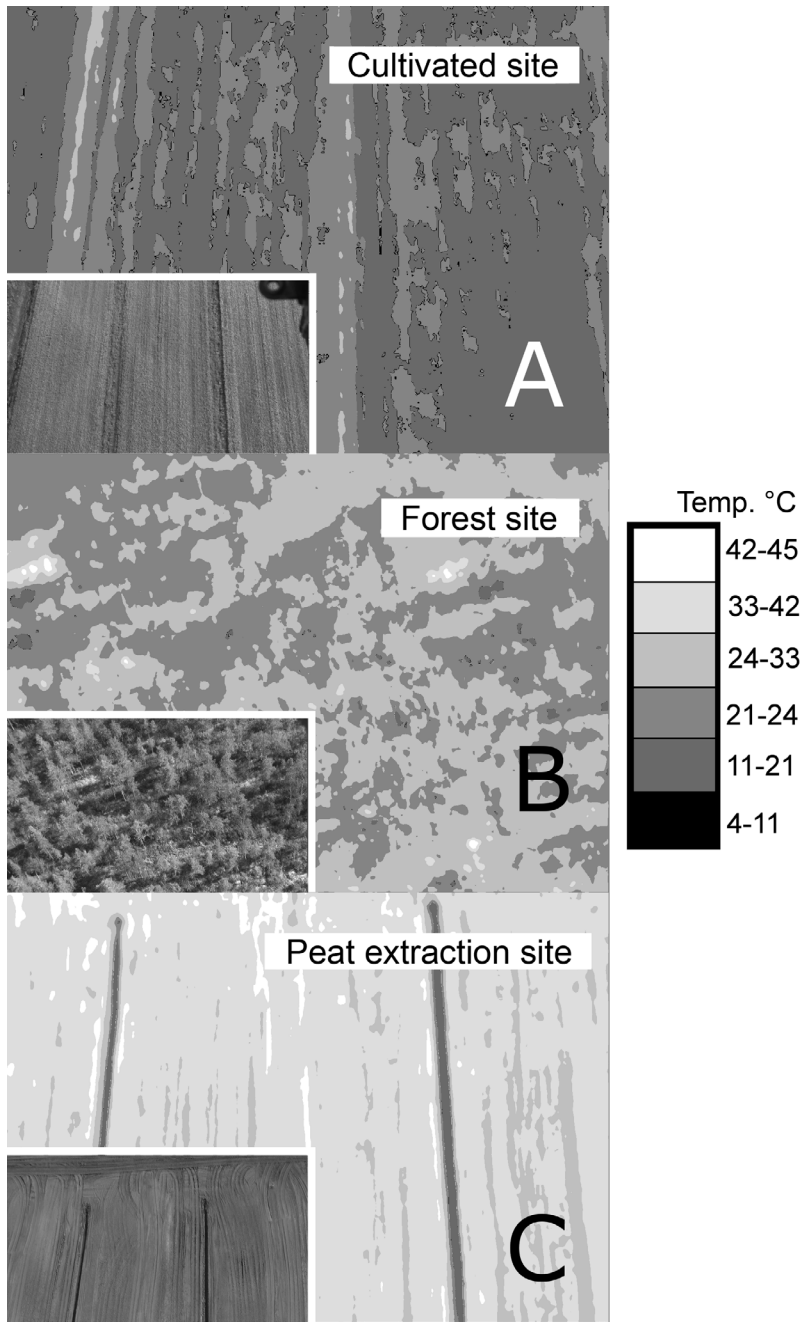


**Appendix**. Infrared photograph of the drained study sites (A = the cultivated site, B = the forest site, C = the peat-extraction site) taken on a sunny day in summer 2013. Normal photos of the same areas are included as smaller pictures. Ditches show up as vertical warmer areas in the cultivated site and vertical cooler areas in the peat-extraction site.